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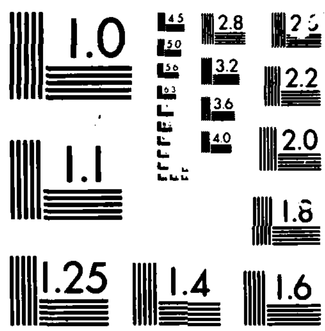

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PULL-OFF FORCES FOR ADHESIVE TAPES

by

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An analysis is given of the force F required to pull an adhesive tape of unit width away from a rigid substrate in terms of the strength G_a of adhesion, the tensile modulus E of the tape, and its thickness t. Measurements are reported for several commercial adhesive tapes and compared with the predictions of the theory. Excellent agreement is

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obtained, suggesting that the theory is basically correct. Attention is drawn to the unusual form of the dependence of the failure force F upon the work G_a of detachment and the resistance Et of the tape to stretching in this case: $F^4 \propto Et\, G_a^{\,3}$. Even though the tape is assumed to be linearly-elastic, the markedly non-linear (cubic) relation between force F and displacement δ of the tape away from the substrate leads to this unusual result. Differences observed in G_a from pull-off and from 90° peeling experiments are tentatively attributed to additional energy losses in the latter case due to the severe bending deformations imposed on the tape as it is peeled away.

variation

delta

Keywords:

FLD 19

1. Introduction

When adhesive tapes are pulled away from a rigid substrate, as shown schematically in Figure 1, the force required depends upon both the strength of adhesion and the resistance of the tape to stretching. Although these two factors are obviously significant, no previous analysis of their relative importance is known to the present authors. A simple theoretical treatment is therefore given below relating the pull-off force $\underline{F}$ to the strength of adhesion, characterized by the work $\underline{G_a}$ required to detach unit area of adhering tape from the substrate, and the effective tensile (Young's) modulus $\underline{E}$ of the tape, assumed for simplicity to be linearly elastic. Measurements with various commercial tapes are then reported, and compared with the theoretical predictions.

Because of the simplicity of this experiment, and the ready way in which values of $\underline{G_a}$ and $\underline{E}$ can be deduced from it, it may have potential value as a routine test method for adhesive tapes. This is particularly the case for tapes that are commonly used to secure items to a rigid base, when the pull-off force $\underline{F}$ represents an important service parameter.

Quite apart from any potential practical value, the analysis of the pull-off force $\underline{F}$ has some scientific interest, for two reasons. It demonstrates once again the power of simple energy considerations in fracture mechanics, using a characteristic value of the detachment energy $\underline{G_a}$ as the criterion for debonding (1-6). And the pull-off force $\underline{F}$ is found to be neither proportional to $\underline{G_a}$, as might at first be expected and is, indeed, observed in simple peeling experiments (7-9), nor is it proportional to $(\underline{EG_a})^{\frac{1}{2}}$ as is found in many linearly-elastic ("Griffith") systems where energy is expended in deforming layers after debonding them (10-13). Instead, it is found to be proportional to $(\underline{EG_a{}^3})^{\frac{1}{4}}$, a result

which emerges directly from the analysis as a consequence of the particular relation which holds between the force F and the corresponding elastic displacement δ of the tape when no further debonding occurs; $F \propto \delta^3$; even though the components are assumed to be linearly-elastic (14). This is the first time to the authors' knowledge that other possible types of dependence of the failure force F upon E and G_a have been pointed out.

2. Theoretical considerations

(i) Elastic behavior

A sketch of an adhesive tape being pulled away from a rigid substrate is shown in Figure 1. The tensile strain e in the tape is obtained in terms of the angle θ between the detached part of the tape and the substrate surface from geometrical considerations:

$$e = \sec\theta - 1. \tag{1}$$

Thus, when θ is small,

$$e \simeq \theta^2/2. \tag{2}$$

The tensile force F' in the detached part of the tape is related to the applied pull-off force F,

$$F = 2F' \sin\theta. \tag{3}$$

Assuming that the tape is linearly-elastic, with an effective value of tensile (Young's) modulus E, the force F' is given by Ewt, where w and t are the width and thickness of the tape.

Thus,

$$F = 2Ewt \sin\theta\,(\sec\theta - 1). \tag{4}$$

When θ is small, this simplifies to yield (14):

$$F = Ewt\,\theta^3. \tag{5}$$

(ii) Conditions for detachment

We now consider the energy changes that take place for further detachment by a distance $2\,\Delta c$ (Figure 1). Work supplied by the pull-off force F is $F \tan\theta\,\Delta c$. Work expended in detachment is $2G_a w\Delta c$, and work expended in stretching the newly-detached parts of the tape is $Ee^2wt\Delta c = Ewt(\sec\theta - 1)^2\Delta c$. By equating the work supplied to the total work expended we obtain

$$F \tan\theta = 2G_a w + Ewt\,(\sec\theta - 1)^2. \qquad (6)$$

On substituting for F from equation (4) and rearranging:

$$G_a/Et = \tfrac{1}{2}\tan^2\theta + \cos\theta - 1. \qquad (7)$$

When θ is small this becomes

$$G_a/Et = 3\theta^4/8. \qquad (8)$$

Equations 7 and 8 give the work G_a of detachment in terms of the angle θ between the detached tape and the substrate. In terms of the pull-off force F and angle θ from equation 5,

$$G_a = (3/8)\,F\,\theta/w, \qquad (9)$$

and in terms of F and the tape modulus E,

$$F/w = (8G_a/3)^{3/4}\,(Et)^{1/4}. \qquad (10)$$

These results are valid only at small values of θ, because they depend upon the approximations leading to equations 5 and 8. The exact result for F is given in parametric form by equations 4 and 7. However, even for values of the angle θ as large as 45° the error is less than 10 per cent when G_a is calculated from equation 10 because of compensating errors in equations 5 and 8. On the other hand, if G_a is calculated from measurements of θ by means of equation 8 or 9, then the error is about

10 per cent when $\underline{\theta}$ is 25° and becomes rapidly greater for larger angles.

In the following parts of the paper experimental measurements of the pull-off force $\underline{F}$ and angle $\underline{\theta}$ are described for some pressure-sensitive adhesive tapes and compared with the theoretical relations given above.

3. Experimental details

(i) Materials

Several commercial pressure-sensitive adhesive tapes were employed in the experiments:

A, a vinyl plastic electrical tape, 19 mm wide and about 0.235 mm thick (3M Company, denoted 88)

B, a window film mounting tape, 12.7 mm wide and about 0.105 mm thick (3M Company, Catalog No. 2145)

C, a relatively thick, soft, extensible mounting tape, 12.7 mm wide and about 1.34 mm thick (3M Company, Catalog No. 110)

D, a clear tape, 25.4 mm wide and about 0.14 mm thick (Manco Tape Inc., denoted All-Weather Clear Tape)

E, a paper-based masking tape, 25.4 mm wide and about 0.145 mm thick (Tuck Tape)

(ii) Tensile stress-strain relations

Measurements were made of the relations between tensile force per unit width and extension for the first three tapes, using strips about 300 mm long, stretched at 5 mm/min. They were approximately linear for tapes A and C over the range 0-20 per cent extension, Figure 2a, but highly non-linear for tape B, which under went plastic yielding at about 3 per cent extension, Figure 2b. Values of the average tensile strains set up during pull-off experiments from glass were deduced from the measured pull-off angles θ by means of equation 2; they were 5.0 per cent for tape A, 2.3 per cent for tape B and 13.3 per cent for tape C. Effective values of Et were calculated from the corresponding tensile stresses of 3.50 kN/m, 85.5 kN/m and 1.25 kN/m, respectively. (Using the measured tape thicknesses t, these results correspond

to effective values of tensile modulus E of 15 MPa, 820 MPa and 0.92 MPa for tapes A, B and C.)

Because the detachment forces with a Teflon substrate were significantly smaller for Tapes B and C, the average tensile strains were also smaller, about 0.8 per cent and about 3.8 per cent, respectively, and the effective values of Et were correspondingly somewhat larger than before, about 105 kN/m and about 1.5 kN/m, due to the non-linear stress-strain relations.

(iii) Measurement of pull-off forces

Samples of tape about 350 mm long were applied to a rigid horizontal substrate, a polished glass plate or a smooth Teflon plate, previously cleaned with acetone. A stiff wire loop, trapped between the center of the strip of tape and the substrate, was then used to pull the tape away. Pull-off forces F and angles θ were measured as shown schematically in Figure 1, with a tensile testing machine. To prevent the tape from slipping along the substrate during pull-off, the ends were wrapped around the ends of the substrate plate and in some instances secured there by tape clamps. In order to vary the effective stiffness Et without changing the detachment energy G_a, up to ten layers of tape were applied, one on top of another. On the other hand, by using the same tapes on two different substrates, glass and Teflon, it was hoped to vary G_a substantially without changing the effective stiffness of the tape.

As the tape began to pull away from the substrate the applied force F rose to a relatively-large starting value and then fell to a value about

30 per cent lower and remained at this level as detachment continued over long distances. Steady-state values of $\underline{F}$ and the pull-off angle $\underline{\theta}$ have been taken here as representative of pull-off at a constant rate of detachment. The initial surge is ascribed to higher start-up velocities.

All experiments were carried out at ambient temperature, about 24°C, and with a crosshead speed of 83 μm/s.

(iv) Independent measurements of G_a

Measurements were made of the force $\underline{F}$ required to peel tapes away from the substrates at an angle of 90°, Figure 3, and at various speeds $\underline{v}$ in the range 0.1 to 1 mm/s. Values of detachment energy G_a were then calculated:

$$G_a = F/w. \tag{11}$$

By interpolation, values were obtained appropriate to the speed dc/dt at which debonding took place in the pull-off experiments, where $dc/dt = v / \tan\theta$, Figure 1.

4. Experimental results and discussion

(i) Pull-off forces and angles

Measured values of pull-off force *F* and angle θ are given in Tables 1 and 2. Values of detachment energy G_a calculated from them by means of equation 9 are given in the fourth column of Tables 1 and 2 and values calculated from the pull-off force *F* alone, with the separately-determined value of the effective tensile stiffness *Et* for each tape 1, using equation 10,are given in the fifth column of Tables 1 and 2. These two estimates of G_a are in reasonable agreement with each other in all cases, suggesting that the essential features of the mechanics of pulling away an extensible tape from a rigid substrate are contained in the theoretical treatment. However, they are not generally in good agreement with direct measurements of G_a by peeling away the tape at an angle of 90°, given in the final columns of Tables 1 and 2 for peel velocities equal to the computed rates of advance of the separation front in the pull-off experiments. The discrepancies are significant, and rather different in magnitude for the different tapes. For tapes *A* and *D*, for example, the peel energies are about 2X to 3X the pull-off energy, whereas for tapes *C* and *E* and for tape *B* adhering to Teflon, the peel energy is closer to the pull-off energy. Possible reasons for these differences are discussed later. We note here only that values of detachment energy G_a obtained from pull-off experiments are internally consistent and generally lower than those obtained from peeling experiments.

A striking feature of the present theoretical treatment is the form of the predicted dependence of pull-off force $\underline{F}$ upon the effective thickness of the adhering tape $\underline{t}$; $\underline{F \propto t^{\frac{1}{2}}}$; equation 10. Experimental values of $\underline{F}$ are plotted in Figures 4 and 5 against $\underline{N}^{\frac{1}{2}}$, where $\underline{N}$ is the number of layers of tape applied one on top of another and pulled away together. Clearly, the effective tape thickness $\underline{t}$ is proportional to $\underline{N}$ in these experiments. As can be seen in Figures 4 and 5, accurately linear relations were obtained between $\underline{F}$ and $\underline{N}^{\frac{1}{2}}$ in all cases, in good accord with the theoretical prediction.

A further prediction of the theory is that the product $\underline{F\theta}$ will be independent of the stiffness of the tape, and hence of the thickness $\underline{t}$ or number $\underline{N}$ of layers pulled off together (except insofar as the speed of separation is altered, so that changes are brought about in the detachment energy $\underline{G_a}$ on this account). Values of $\underline{F\theta}$ are plotted in Figures 6, 7 and 8 against the number $\underline{N}$ of adhering layers. They are seen to be substantially constant, independent of $\underline{N}$, even though $\underline{F}$ and $\underline{\theta}$ vary separately with $\underline{N}$ to a significant extent, Tables 1 and 2.

It is interesting to note that the apparent detachment energy $\underline{G_a}$, given by $\underline{3F\theta/8w}$, was approximately the same for Tape $\underline{A}$ pulled away from a glass or a Teflon surface. In contrast, for Tapes $\underline{B}$ and $\underline{C}$ the detachment energies for a Teflon surface were only about 25 per cent and 15 per cent of those for a glass surface, in accord with the lower wettability expected for Teflon. The adhesion of Tape $\underline{A}$ must be attributed largely to its rheological features rather than to selective wettability.

(ii) Discrepancies in $\underline{G_a}$

Several possible reasons may be adduced for the observed discrepancies in the detachment energy $\underline{G_a}$ from pull-off and from peeling experiments. In the first place, equations 9 and 10 are based on the assumption that the pull-off angle $\underline{\theta}$ is small. This is not always a valid assumption, expecially for strongly-adhering, easily-stretched tapes, Tables 1 and 2. However, the values obtained from equations 9 and 10 are in good agreement, even though the assumption of small $\underline{\theta}$ is more stringent in the first case. Also, the discrepancy is not markedly reduced when many layers of tape are detached together and the angle $\underline{\theta}$ is much smaller. Finally, the size of the discrepancy does not correlate well with the magnitude of $\underline{\theta}$. We conclude that the simplifying assumption that $\underline{\theta}$ is small is not responsible for the observed discrepancies.

A second possible cause is non-linear elastic behavior of the tapes in tension. In contrast to the assumed linear elastic response, the tapes followed a non-linear relation between tensile force and elongation to various degrees, Figure 2, so that the effective stiffness $\underline{Et}$ at small strains and pull-off angles was greater than at large ones. It seems probable that the use of an average value of $\underline{Et}$ in calculating $\underline{G_a}$ from pull-off experiments is responsible for a small but systematic change in the values obtained as the number of layers was increased and the imposed tensile strain was correspondingly reduced. This feature should be most pronounced for tapes which yield in tension, Tapes $\underline{B}$ and $\underline{D}$, and at large values of $\underline{\theta}$, i.e; for pull-off of single layers.

But these results do not seem to be particularly anomalous, Tables 1 and 2. It must therefore be concluded that the simplifying assumption of linearly-elastic behavior, although quite inadequate for tapes which undergo plastic yielding, was a reasonably satisfactory approximation in most of the experiments reported here.

A third assumption implicit in the theoretical treatment is that work expended in bending the tape away from the substrate is negligible, or at least is the same in both the pull-off and the peeling experiments so that it contributes equally to the values obtained for $\underline{G_a}$. In some circumstances this contribution can be both large and strongly dependent upon the magnitude of the peel angles (15). It would also be expected to depend upon the structure of the tape and hence to vary from one tape to another. Thus, it may be the primary factor responsible for the observed discrepancies in $\underline{G_a}$ from pull-off at small angles and from peeling at 90°, even though the mode of failure appears to be so similar in the two cases. Further work is needed to clarify this point.

5. Conclusions

The predicted dependence of the pull-off force upon the effective stiffness Et of the tape, the number N of layers applied, and the type of substrate used were found to hold reasonably well. In particular, the unusual forms of the predicted dependence upon $(Et)^{1/4}$ and upon $G_a^{3/4}$ appear to be correct. Thus, the pull-off experiment appears to be a simple way of characterizing both the energy G_a required for detaching an adhesive tape at small angles and the effective tensile stiffness of the tape. Moreover, it resembles many service applications of pressure-sensitive tapes. If a tape stretches too much, so that the angle θ becomes unreasonably large (greater than about 30°, say) then two or more layers of tape can be applied and pulled off together. In some instances it was found that the layers did not adhere to each other as well as they adhered to the substrate; the multi-layer method is then not a feasible way of reducing θ to sufficiently small values and the parametric solutions for F must be employed.

Acknowledgements

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Table 1: Detachment from glass

Number of layers N	Pull-off force F/w (N/m)	Pull-off angle θ(rad)	G_a(N/m) From eq.9	From eq.10	From eq.11
		Tape A			
1	217±5	0.42	34	32	95
2	268±10	0.34	34	33.5	100
3	320±10	0.31	37	37	102
4	360±20	0.30	40.5	39.5	104
5	445±20	0.29	48.5	48.5	105
6	455±20	0.27	46	47	107
7	475±20	0.26	46.5	47.5	108
8	545±20	0.255	52	54.5	109
9	550±20	0.245	50.5	53	110
10	558±20	0.235	49	52	112
		Tape B			
1	1585±15	0.36	214	157	290
2	2110±20	0.255	202	183	305
3	2400±155	0.225	202	190	315
4	2665±155	0.20	201	198	320
5	2550±230	0.175	167	174	330
6	2705±230	0.165	167	176	335
7	3170±310	0.165	197	208	335
8	3245±310	0.165	201	205	335
9	3630±310	0.165	225	228	335
10	3475±310	0.165	216	208	335

Table 1 (continued)

Number of layers N	Pull-off force F/w (N/m)	Pull-off angle θ(rad)	G_a(N/m) From eq.9	From eq.10	From eq.11
		Tape C			
1	340±25	0.70	89	83	172
2	400±25	0.59	88.5	82	173
3	480±25	0.56	101	91.5	174
4	585±25	0.56	123	108	174
5	735±25	0.54	149	136	174
6	635±25	0.47	112	105	176
7	740±25	0.445	123	122	176
8	710±25	0.43	114	111	177
9	710±25	0.395	105	107	178
10	790±25	0.375	111	118	179
		Tape D			
1	485±40	0.365	67	59	199
2	580±40	0.28	62	60	207
		Tape E			
1	570±40	0.225	48	42.5	63
2	735±40	0.20	55	47.5	65

Table 2: Detachment from Teflon

Number of layers N	Pull-off force F/w (N/m)	Pull-off angle θ(rad)	$\dot{G}_a$ (N/m) From eq.9	$\dot{G}_a$ (N/m) From eq.10	$\dot{G}_a$ (N/m) From eq.11
		Tape A			
1	238±10	0.40	36	37	80
2	297±10	0.34	38	39.5	83
3	325±10	0.295	36	38.5	86
4	382±15	0.27	39	43.5	88
5	435±15	0.26	42	48	89
6	435±20	0.25	41	45	90
7	470±20	0.24	42.5	48	91
8	510±20	0.24	46	51	91
9	530±20	0.24	48	52	91
10	555±20	0.23	47.5	52.5	92
		Tape B			
1	525±25	0.175	34.5	34	49
2	725±30	0.155	42	41	49
3	850±30	0.14	44.5	44	49
4	1005±30	0.12	45	50	49
5	1080±30	0.12	48.5	51.5	49
6	1145±40	0.115	49.5	52	49
7	1195-40	0.105	47	52.5	49
8	1275±75	0.105	50	54.5	49
9	1275±75	0.105	50	52.5	49
10	1315±75	0.095	47	53	49
		Tape C			
1	89±4	0.42	14.0	13.0	24
2	116±8	0.35	15.2	14.7	24
3	124±8	0.305	14.2	14.1	24
4	151±8	0.28	15.9	16.6	24
5	170±8	0.26	16.6	18.1	24
6	182±8	0.245	16.7	18.6	24
7	185±8	0.22	15.3	18.1	24
8	193±8	0.21	15.2	18.3	24
9	208±8	0.19	14.8	19.6	24
10	228±8	0.185	15.8	21.2	24

Figure Captions

Figure 1. Sketch of the pull-off experiment.

Figure 2. Experimental relations between tensile load per unit width F/w and extension e for selected tapes.
(a) Tapes A and C
(b) Tape B

Figure 3. Peel experiment

Figure 4. Plot of the pull-off force per unit width F/w vs $N^{\frac{1}{4}}$ where N is the number of layers of tape applied one on top of another to a glass substrate and pulled away together.

Figure 5. Plot of the pull-off force per unit width F/w vs $N^{\frac{1}{4}}$ where N is the number of layers of tape applied one on top of another to a Teflon substrate and pulled away together.

Figure 6. Plot of $F\theta/w$ vs N for Tape A adhering to glass (open circles) and to Teflon (filled-in circles).

Figure 7. Plot of $F\theta/w$ vs N for Tape B adhering to glass (open triangles) and to Teflon (filled-in triangles).

Figure 8. Plot of $F\theta/w$ vs N for Tape C adhering to glass (open squares) and to Teflon (filled-in squares).

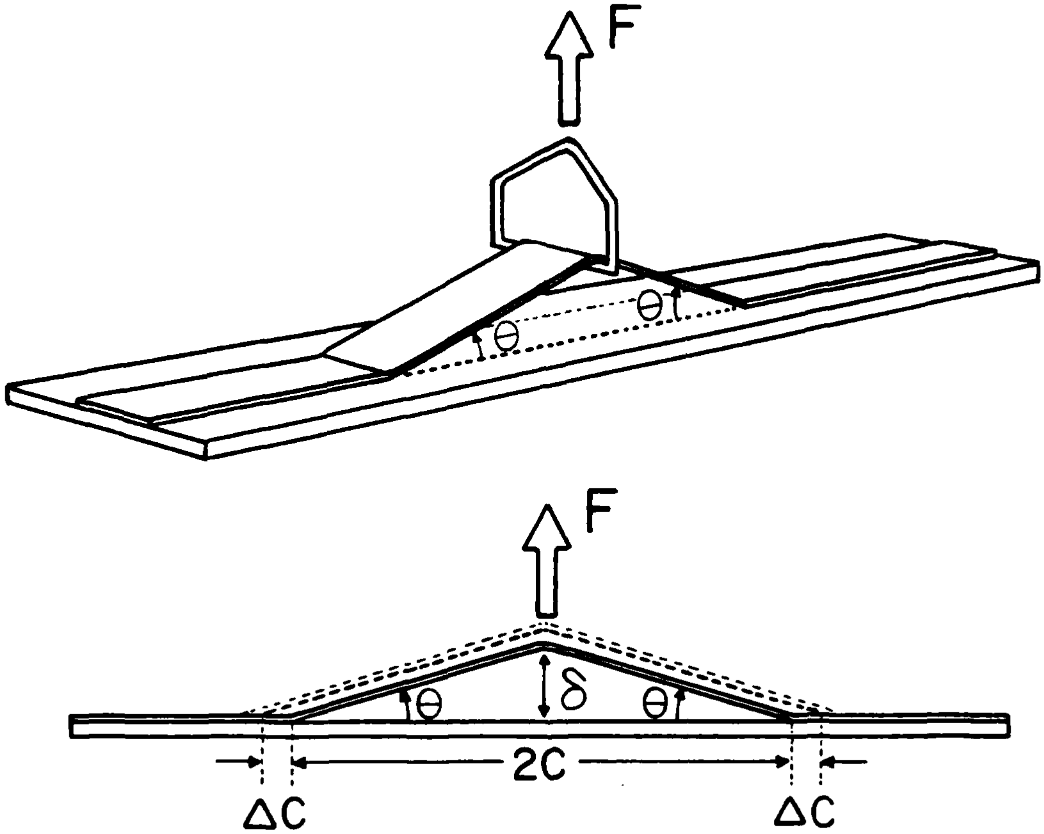


Figure 1

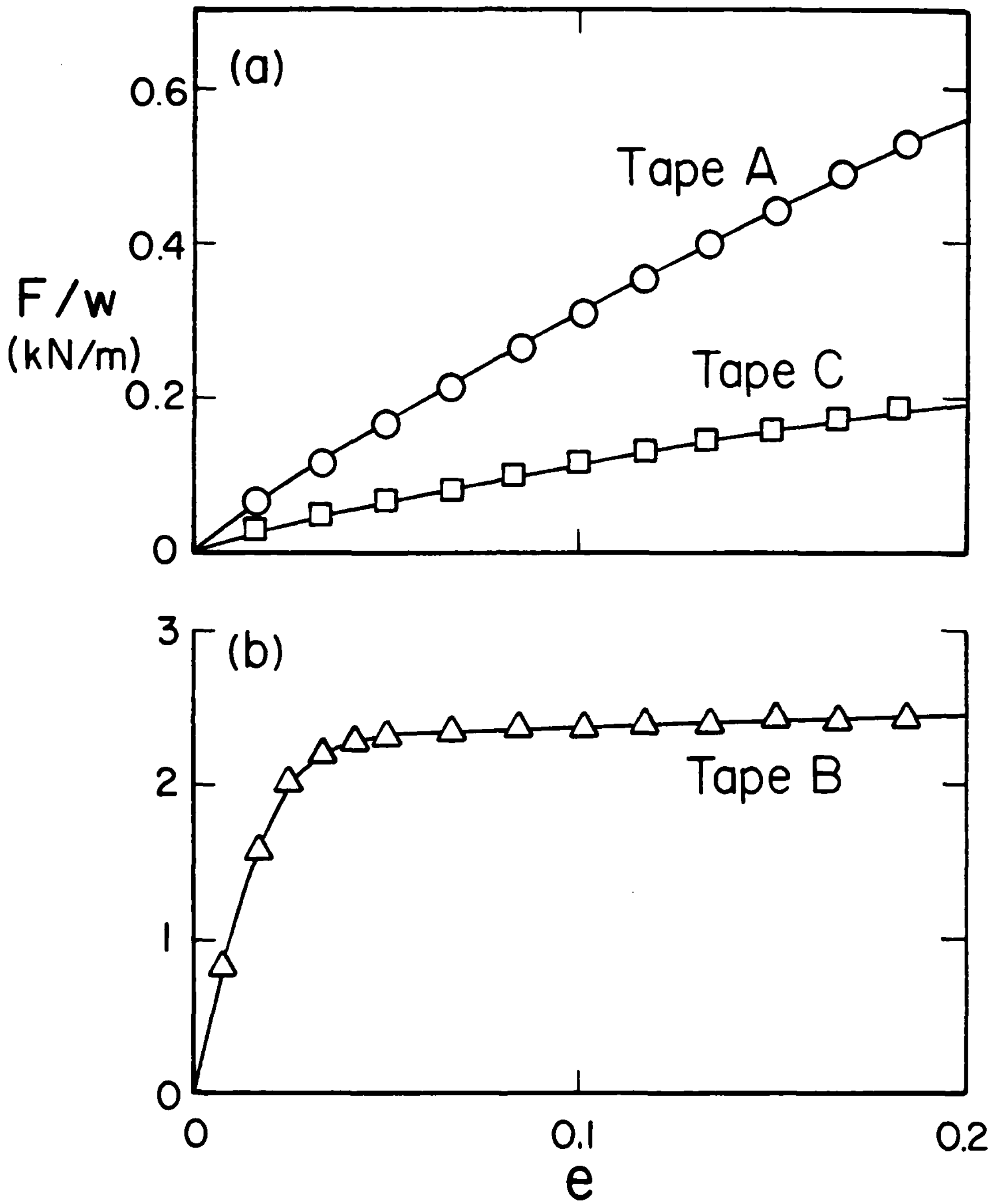
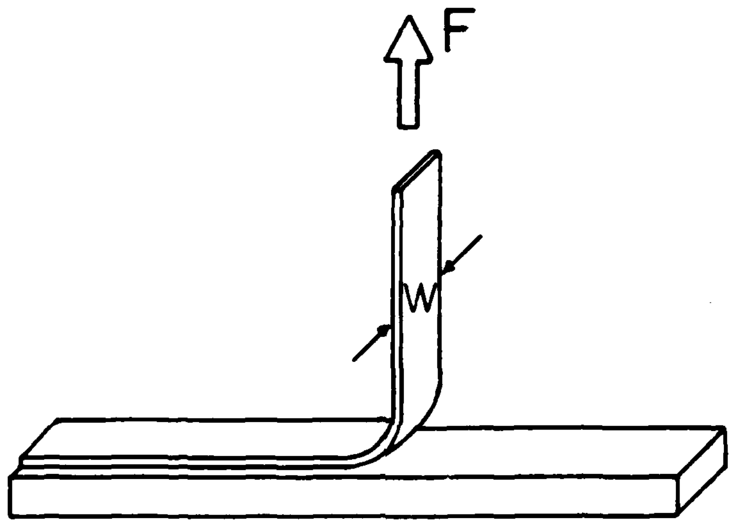


Figure 2



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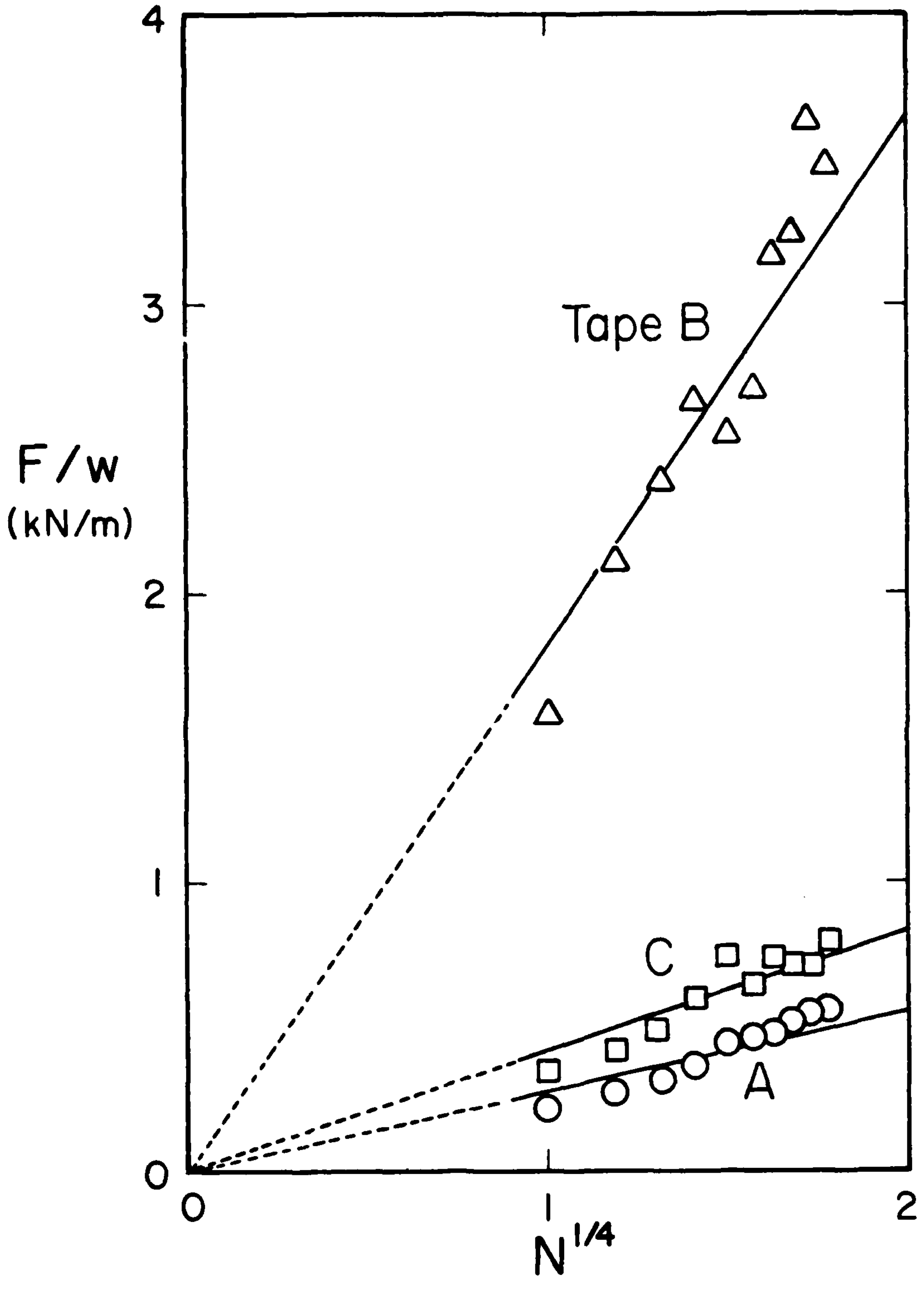


Figure 4

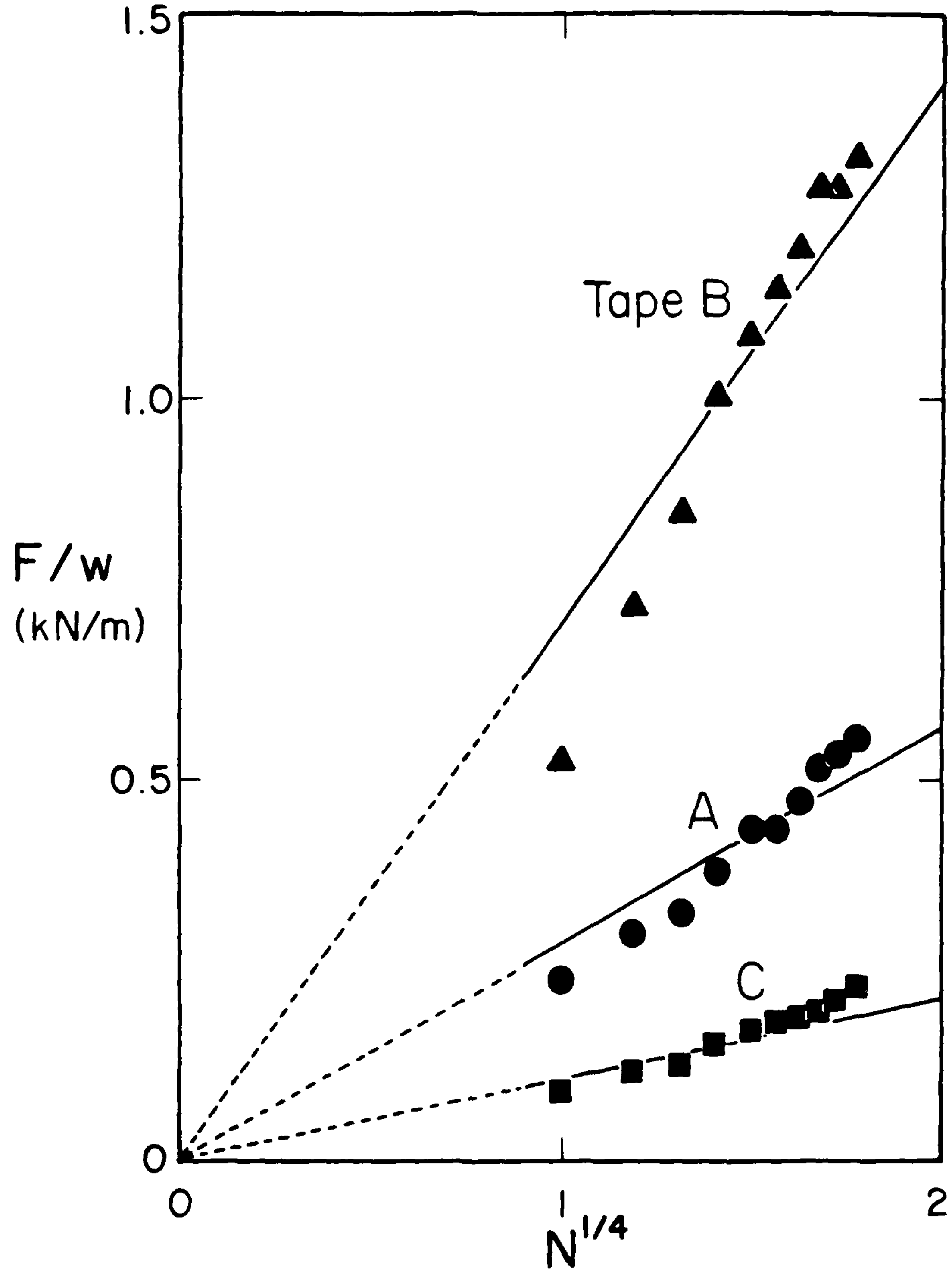


Figure 5

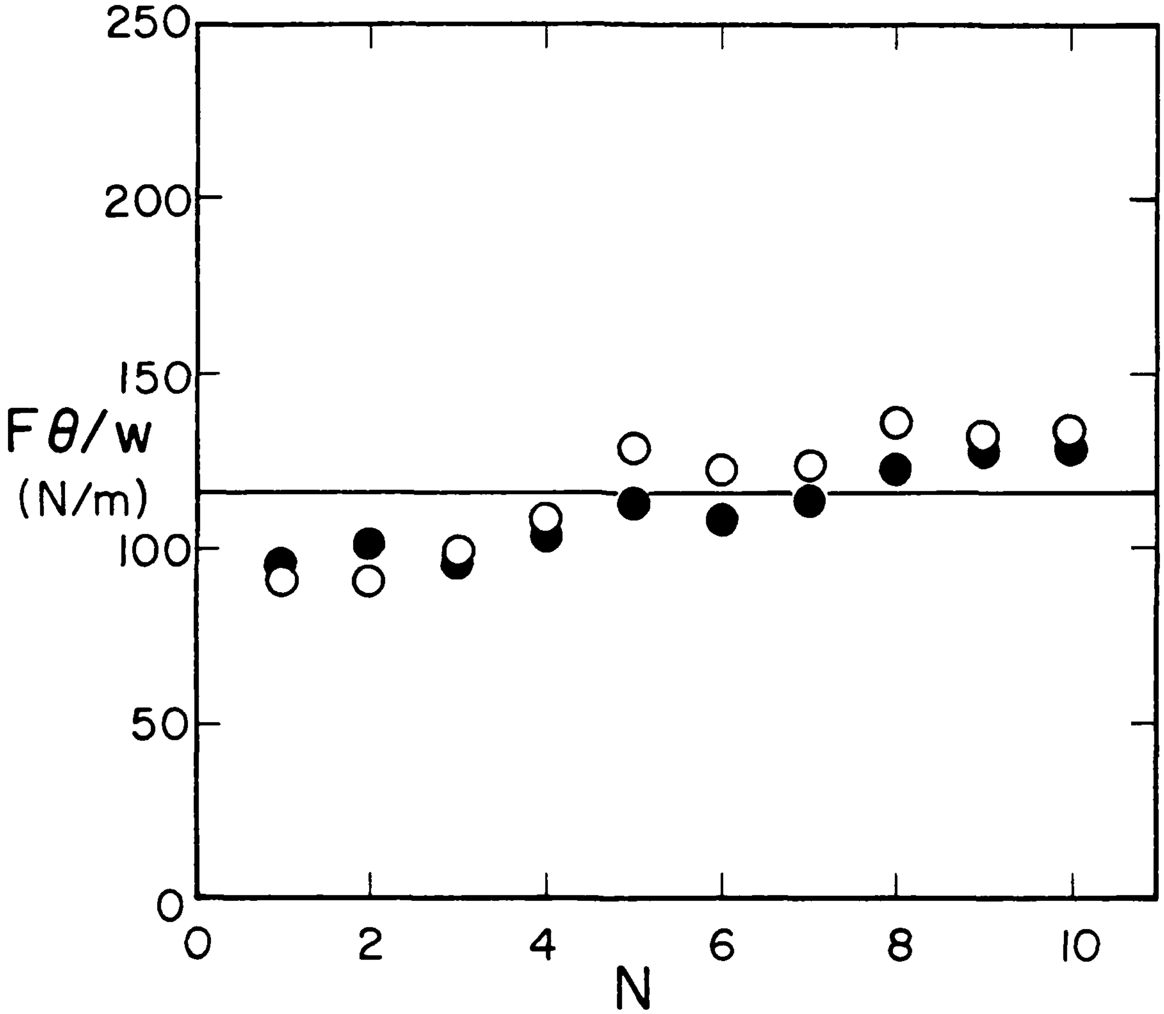


Figure 6

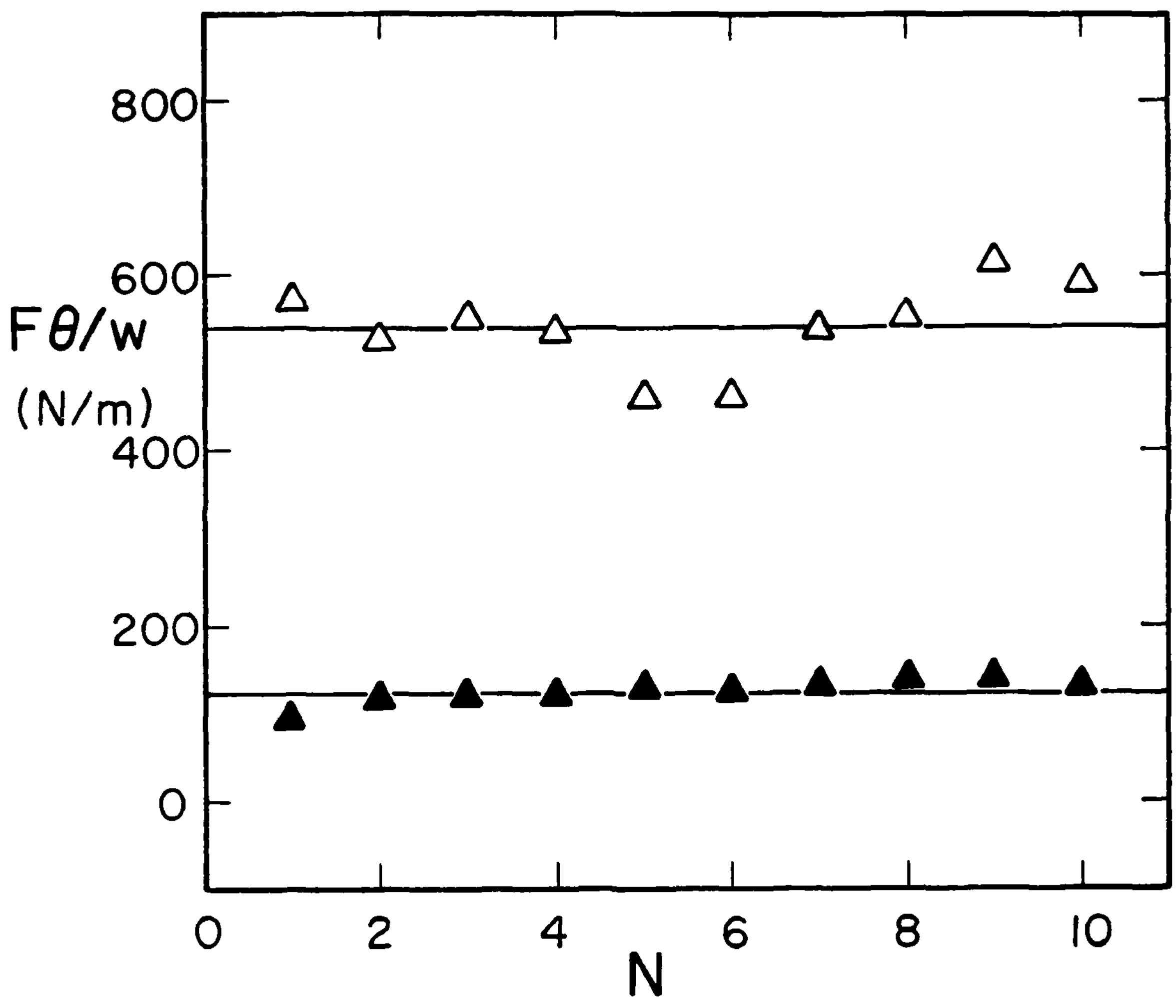
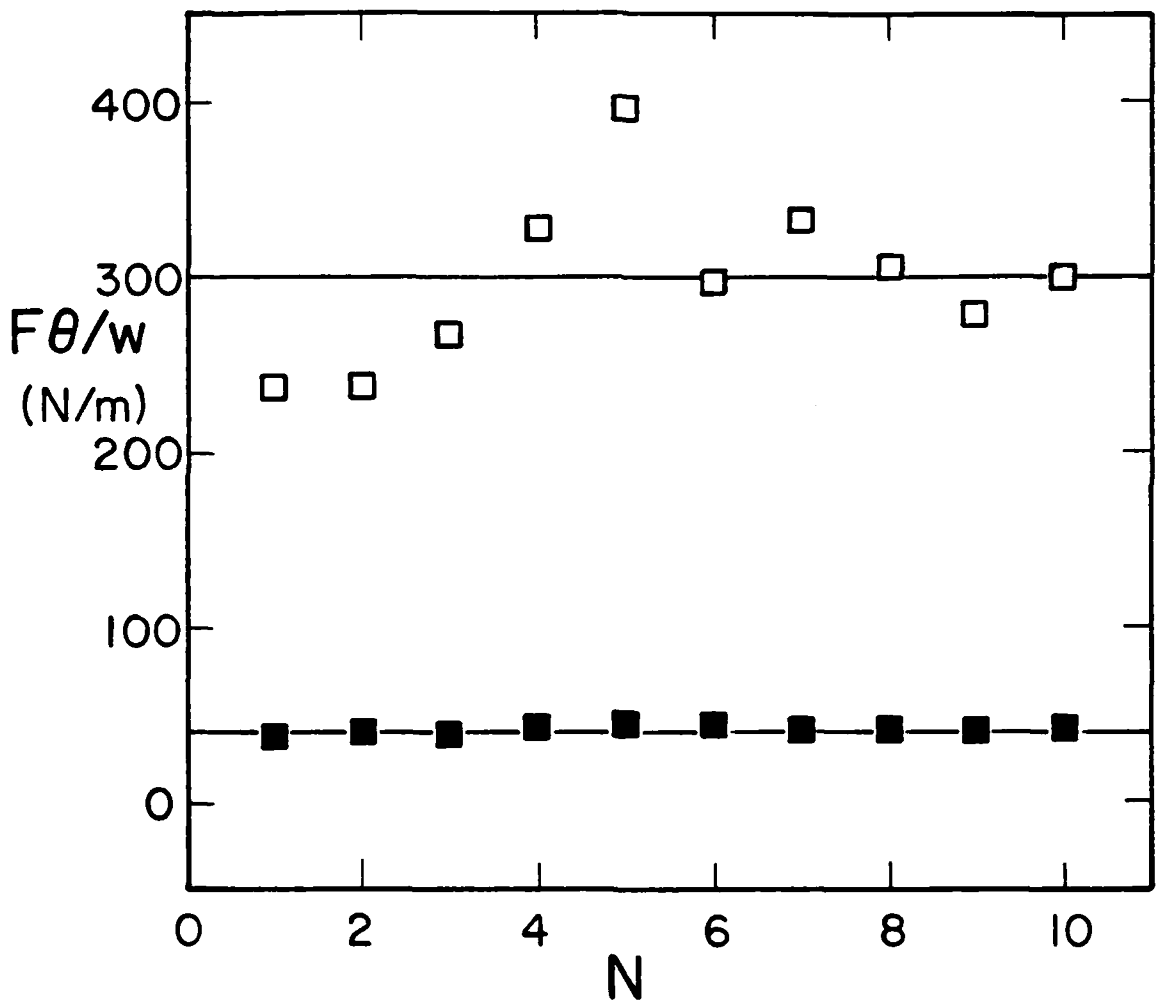


Figure 7



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